

Laddermill sail – a new concept in sailing

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Abstract. A new innovative approach to sailing has been proposed by TU Delft. It allows sailing in any desired direction, including straight into the wind. The concept consists of generating energy with a sky sail and then using it in an electric motor of the ship. The paper describes a mathematical model of laddermill sail.

Keywords: Laddermill, sailing, wind energy

I. INTRODUCTION

A lot of research has been done worldwide in using winds for clean energy production (e.g., [9, 26, 27]). The concept for sustainable energy production called “laddermill” [21] (see fig. 1a, b) is known for 11 years now [22] and refers to the system of kites on one rope that drives the generator as kites pull it. The benefits of this approach to energy production is a low weight, low cost and simplicity of the structure, installation and maintenance [20]. Theoretical investigation promises capabilities of a vast power output. The concept has been successfully tested on a small scale with a single kite and several authors contributed to simulation of the kite systems (e.g., [14, 33]) and a robust controller for this application has been recently published in [24]. This eventually led to the idea of Laddermill sail [7, 19], a ship that is propelled by Laddermill power (see fig. 2).

Laddermill is designed to become an alternative to windmills. It looks like a *ladder* of kites and generates electricity from wind as a *windmill*. When kites pull the rope the winch rotates and dynamo generates energy. Laddermill is a collective name for several designs; a rotating ring [18, 15] is historically the first. A ‘yo-yo’-like system is described in [29] and pumping Laddermill is pictured below. All designs of Laddermill have several benefits in comparison with conventional windmills. At first, they do not have dramatic cost curve due to the absence of blades and a pole; cost increase for larger than 5 MW designs is much more close to linear, in theory making such machines feasible. The required thickness of cable is a limiting factor and probably 100 MW or a bit more would be a technological limit of designs based on conventional Dyneema cables [13]. Next to it is a relatively low cost of installation and even mobility – there is no pole to dig into the ground and no blades to transport. Finally, Laddermill has a choice of altitudes: if there is not much wind on one altitude, it is possible to climb or descent and find an airflow layer with more desirable wind conditions.

Laddermill’s ground station includes all basic parts of a windmill chamber: climatic camera, motor-generator, battery, brakes, etc. The main cable we are using now is made of Dyneema SK-60 fibers, and potentially it can be made of even stronger fibers or even nanoropes of space lift projects. The kites we use now are conventional surfkites because of their long design and exploitation record. However specially designed gliders [3], inflatable [2], twinskin [6] or lightweight [1] kites, parawings [34] and parachutes [8] can produce even better results.

Pumping laddermill operates as follows. At first the first kite is launched into the air. Ground station unreels the rope while the first kite pulls the rest of the kites until they are all in the air. When the kites are considered launched, the ground station switches into dynamo mode and starts generating electricity and charging the battery. The length of the cable when this happens is called starting length. During generating energy the kites are

flying in figures “eight”. Their roll angle is following a harmonic function and yaw angle changes according to the direction of current apparent wind. Kites’ pitch is zero. When the total length of the rope is achieved the kites are depowered, their roll is set to zero, ground station switches into motor mode and the rope is reeled back in to the starting length. By depowering we mean that angle of attack is set to zero lift value (approximately -6 degrees for the chosen kite) by controlling pitch. After that the cycle repeats.

Thus, some of the basic design parameters of a pumping laddermill include aerodynamic coefficients, areas and masses of kites, their number and distances between them along the cable, starting and total cable length, stiffness and breaking strength. The control parameters that determine Euler angles in each moment of time are reel out and reel in speed, period and magnitude of one figure “8”.

Recently kites has earned an increasing attention of researchers. A few methods for addressing stability of kites and parachutes are presented in [16, 28, 31]. However, being primarily design choice tools, they are not suited for robust control. Possible kite control actuators are shown in [5, 6, 12]. Among recent optimization studies about kites is a design optimization paper [11], model-predictive control studies [10, 12], [4] and [32] are in different stages of preparation for publishing. Receding horizon and Lyapunov’s parameters methods are used in all of them while control functions and optimization features are different: [4] and [32] formulate fast control for equations of motion while [10] employs Lagrange equations and full scale control. Control functions in [4, 32] are roll, lift aerodynamic coefficient and cable length, and in [10] – roll, attack angle and cable length.

II. METHODS

A. Mathematical model of Laddermill sail

The Laddermill is a flexible multi-body structure consisting of the kites and the cable. Because of negligible deformations of the arc the kites has been simulated as rigid bodies with surf kite’s airfoil in cross-section. Although techniques like flying in circles [30] allow obtaining aerodynamic coefficients, we found them for a surfkite from simulation of the airflow around surfkite’s airfoil (see figs. 3, 4). The cable is considered elastic, thin and light. Three dimensional equations of motion in the Earth-fixed reference frame (“E”) are written as in [25]:

$$\dot{\mathbf{v}} = \frac{1}{m}(\mathbf{D} + \mathbf{L} - \mathbf{T}_j + \mathbf{T}_{j+1}) + \mathbf{g}, \quad (1)$$

$$\dot{\mathbf{r}}_j = \mathbf{v}_j, \quad (2)$$

$$\mathbf{D} = -\frac{1}{2}\rho S c_D \mathbf{V} \mathbf{V}, \quad (3)$$

$$\mathbf{L} = \frac{1}{2}\rho S c_L \mathbf{V} \boldsymbol{\Phi}^{BE}(\mathbf{d}) \times \mathbf{V}, \quad (4)$$

$$\mathbf{T} = \frac{EA(R - R_0)\mathbf{r}}{R_0 r}, \quad (5)$$

$$\mathbf{V} = \mathbf{v} - \mathbf{w}, \quad \mathbf{R}_j = \mathbf{r}_{j-1} - \mathbf{r}_j \quad (6)$$

here j is the number of the kite (from 1 to N),

i is the number of coordinate (from 1 to 3),

$\mathbf{r} = (r_1, r_2, r_3)$ and $\mathbf{V} = (v_1, v_2, v_3)$ are the position and velocity of the kite relative to the ground,

$\mathbf{R}_j = \mathbf{r}_j - \mathbf{r}_{j-1}$ is the vector pointing from the kite to the nearest element of the cable,

$\mathbf{w} = (w_1, w_2, w_3)$ is the wind velocity,
 $m, S, c_D,$ and c_L are the kite's mass, projected area and aerodynamic coefficients,
 $\mathbf{d} = (d_1, d_2, d_3)$ is a unit vector pointing from the left wing of the kite to the right one;
the three attitude angles (roll ϕ , pitch θ and yaw ψ) affect the components of vector \mathbf{d} in Earth-fixed reference frame [17],
 \mathbf{D}, \mathbf{L} and \mathbf{T} are the forces of drag, lift and tension respectively,
 Φ^{BE} is rotation matrix that converts kite's wingspan vector \mathbf{d} from body-fixed ("B") into Earth-fixed ("E") reference frame:

$$\begin{aligned} d_1^E &= \cos \phi \cos \psi d_1^B + \cos \phi \sin \psi d_2^B - \sin \phi d_3^B, \\ d_2^E &= (\sin \theta \sin \phi \cos \psi - \cos \theta \sin \psi) d_1^B + (\sin \theta \sin \phi \sin \psi + \cos \theta \cos \psi) d_2^B + \sin \theta \cos \phi d_3^B, \\ d_3^E &= (\cos \theta \sin \phi \cos \psi + \sin \theta \sin \psi) d_1^B + (\cos \theta \sin \phi \sin \psi - \sin \theta \cos \psi) d_2^B + \cos \theta \cos \phi d_3^B. \end{aligned}$$

There are also constraints on how fast control can be executed:

$$\omega_0 < \dot{\mathbf{u}}(t) < \omega_1 \quad (7)$$

with the practical limit for each angular ω evaluated as $6\pi/S$. Thus, a 6 m^2 kite can execute a complete turn in 2 seconds and 20 m^2 requires almost 7 seconds to turn.

The kite is steered by changing roll. This is possible because roll directly influences the direction of lift. Yaw is changing according to the direction of apparent wind because the surfkite always tends to turn into flight direction, it never flies with it's wing or trailing edge forward. Depowering is realized by pitching:

$$\phi(t) = u_1(t) \quad (8)$$

$$\theta(t) = \alpha(t) \quad (9)$$

$$\psi(t) = \langle (\mathbf{v} - \mathbf{w}, \mathbf{Ox}^E) \quad (10)$$

The cable between the kites doesn't play significant role so it is neglected with its parameters added to the kites. The cable between the boat and the lowest kite is treated as a single body with no lift.

The boat is considered a single rigid body and no wave or maritime processes are taken into account:

$$\dot{\mathbf{v}}_b = \frac{1}{m} (\mathbf{D} + \mathbf{T}_1 + \mathbf{F}(P, \gamma) + \mathbf{B}) + \mathbf{g} \quad (11)$$

$$\dot{\mathbf{r}}_b = \mathbf{v}_b \quad (12)$$

here \mathbf{F} is ship's thrust, a function of power generated by kites and \mathbf{B} is Archimedes force, a function of how deep the ship is in the water. In unlikely situation of the boat flying out of the water both are zero. The angle γ gives the course of the boat.

Equations of motion (1)-(8) are completed with initial conditions:

$$\mathbf{v}_{j0} = \mathbf{v}_b = 0, \quad \mathbf{r}_j = \mathbf{r}_b = 0, \quad j=1,2,\dots,N \quad (13)$$

Ship's power curve and hull shape were taken from [23]. The boat also has a backup diesel engine: when power becomes negative it's amount is calculated separately:

$$P = T_1 v_c \quad (14)$$

$$E = - \int_{t_0}^{t_1} P dt, \quad P < 0 \quad (15)$$

Sometimes the kites pull the boat sideward so the boat needs a feedback loop controller to follow the course.

B. Laddermill sail control

Laddermill control cycle is following:

- 1) Launch the kites
 - a) Launch the first kite when time reaches t_0
 - b) Reel out the rope
 - c) Attach the next kite (takes some time)
 - d) Repeat (a) – (c) until all kites are in the air
 - e) Reel out the cable to reach operating altitude
- 2) Generate energy
 - a) Reel out. Fly the kites in such a way that cable tension is as high as possible
 - b) Reel in. Depower the kites and fly them in such a way that cable tension is as low as possible
 - c) Repeat (a) – (b) until the time is over
- 3) Retrieve the kites (same as launch in mirror order)
- 4) Stop the boat

C. Environment

The gravity and water density (fresh water, 15 °C) are standard (9,80665 m/s², 1000 kg/m³), air density is following International Standard Atmosphere [17] (15 °C, 101325 Pa at the ground level) and wind profile over altitude is taken as a 20 years average of KNMI (Royal Dutch Meteorological Institute) data (see fig. 5) [21]. Water currents are not taken into account.

III. RESULTS AND DISCUSSION

Sample screenshot of the program is shown on fig. 6. The lowest line is trajectory of the boat, the higher lines are trajectories of the kites. In the beginning of trajectory to the right the kites make arc movements when the cable stops reeling out and it's length remains constant while the next kite is attached. There is also a small push when the cable below the kites starts reeling out. After reaching operating altitude Laddermill starts making rapid movements in the boat's lateral plane so that the tension of the cable is increased. After all cable is reeled out the kites depower and the cable is reeled in. If this phase starts when the kites are not strictly in the longitudinal plane of the ship there will be a sideward component to the tension which will pull the ship off the course. Because of a very simple boat controller (all Laddermill energy is spent directly on propulsion) boat's propeller doesn't work during reeling in and the boat returns to it's course only after the kites start producing energy again.

The following values of parameters have been chosen for program run:

Environment:

Wind strength at sea level – 15 m/s

Wind angle – 0°

Simulation time step – 10^{-3} s

Laddermill sail design:

Boat

Laddermill sail overall efficiency – 50% (0.5)

Tonnage – 60 tons (60,000 kg)

Sc_D – 1,969 m²

Boat stop speed – 1 knot (0.5 m/s) – end simulation condition

Boat course – 180° (straight into the wind)

Cable

Cable density – 900 kg/m³

Cable radius – 3,5 mm

Cable stiffness – 1340625 N

Cable strength – 42000 N

Kite spacing – 15 m

Kites

Number of kites – 5

Kite mass (including cable between kites) – 5 kg

Kite area (including cable between kites) – 20 m²

Kite airfoil – surfkite with aspect ratio 3

Laddermill control:

Launch

Start launch time – 0 s

Launch delay, per kite – 1 s

Operation

Starting cable length – 50 m

Total cable length – 225 m

Reel out speed – 5 m/s

Reel in speed – -10 m/s

Period of angle control – 10 s

Magnitude of angle control – 45°

(for roll control) yaw speed – 2,25 rpm (0,235 rad/s)

(for yaw control) feedback weight – $0.01 \cdot \text{Time step}$

(for yaw control) weight of velocity turn – $0.1 \cdot \text{Time step}$

Parking

Parking time – 120 s

Parking delay, per kite – 1 s

Fig. 7 show the distance traveled by the boat. Fig. 8 shows the boat speed. The simple power controller is responsible for the jumps. Figs. 9 and 10 show kite's ground speed and air speed respectively. Fig. 11 shows trajectory of the highest kite during the 20 seconds in the middle of reeling out phase. Figs. 12-14 show the angles of roll, pitch and yaw of the highest kite during one cycle of reeling out and in and the beginning of another one.

IV. CONCLUSION

A mathematical model of laddermill sail has been developed. It allows modeling full cycle of laddermill sail operation and gives a first, preliminary positive answer on a question about feasibility of the system.

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PICTURES



(a)



(b)

Fig. 1. Drawings of Laddermill. Left – schematic drawing by day (a), right – artistic drawing by night (b).



Fig. 2. Artistic drawing of a Laddermill sail [4]

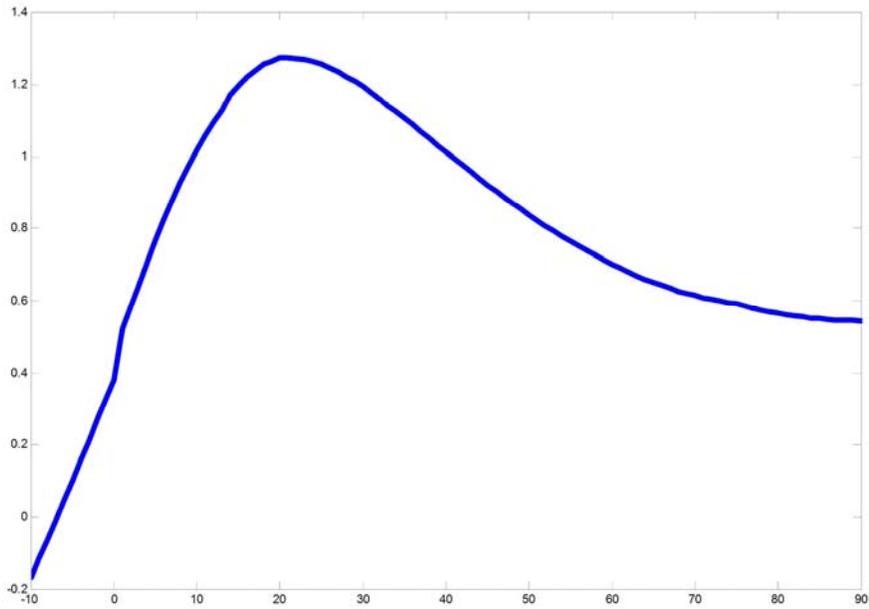


Fig. 3. Lift over attack angle for surfkite's airfoil

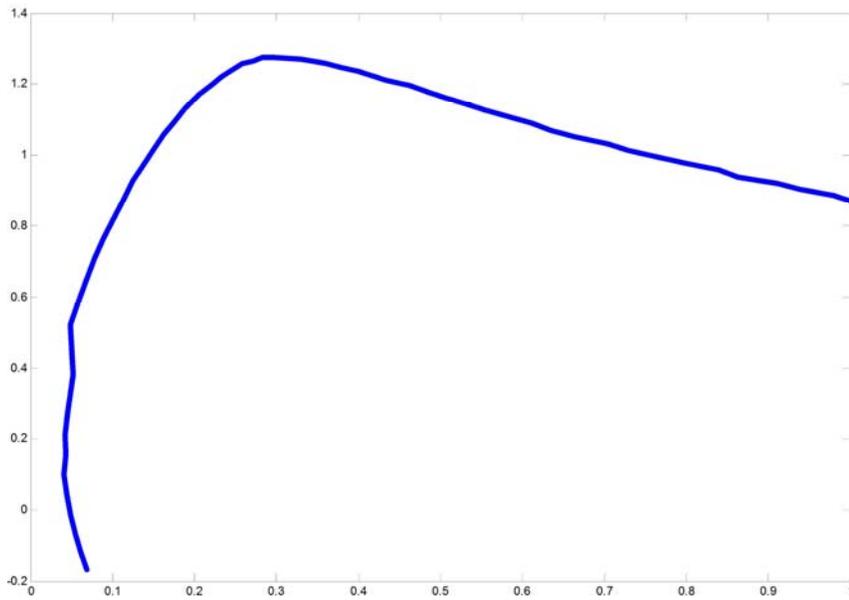


Fig. 4. Lift-drag polar for surfkite's airfoil

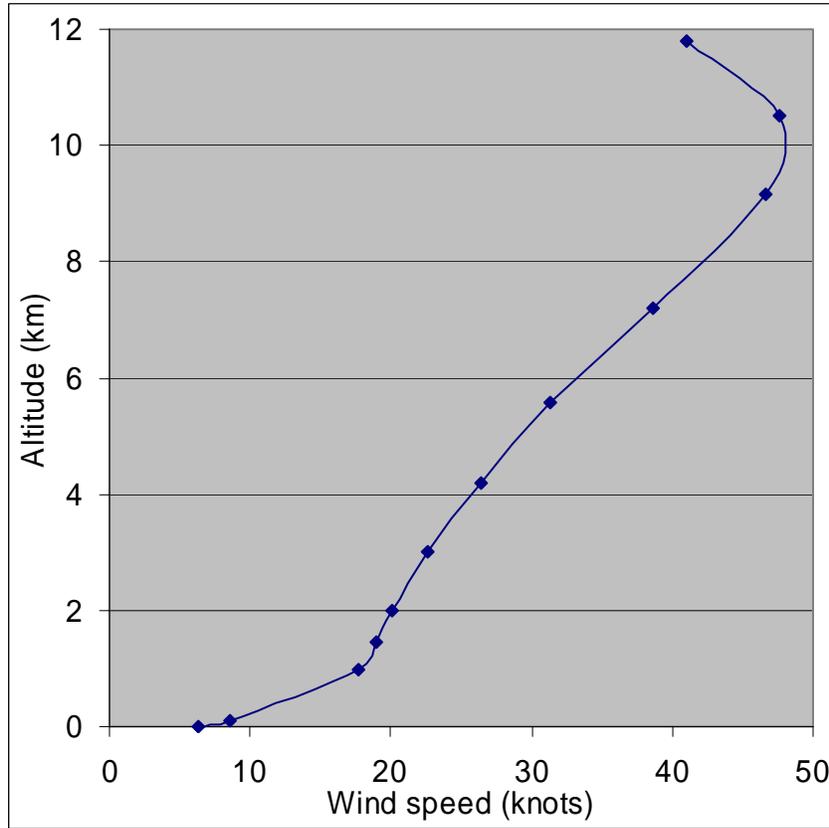


Fig. 5. Average wind speed over altitude according to the data of KNMI.

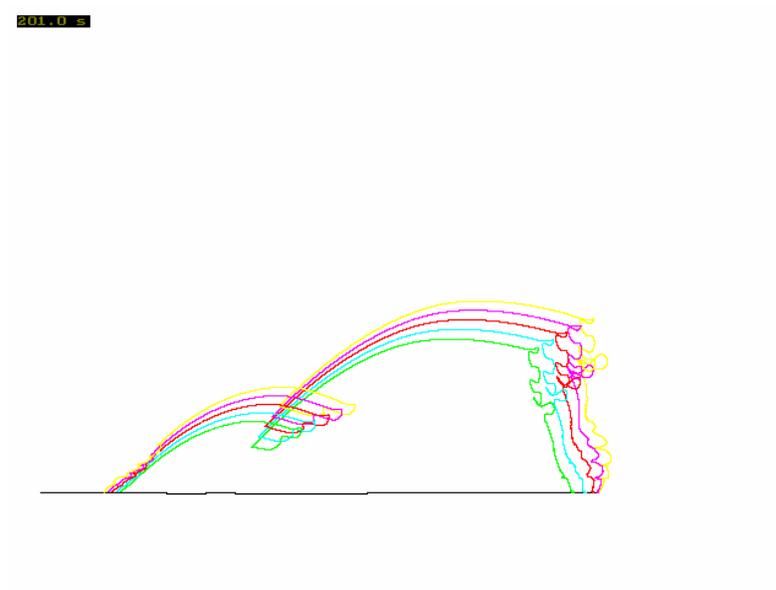


Fig. 6. Sample screenshot of the program

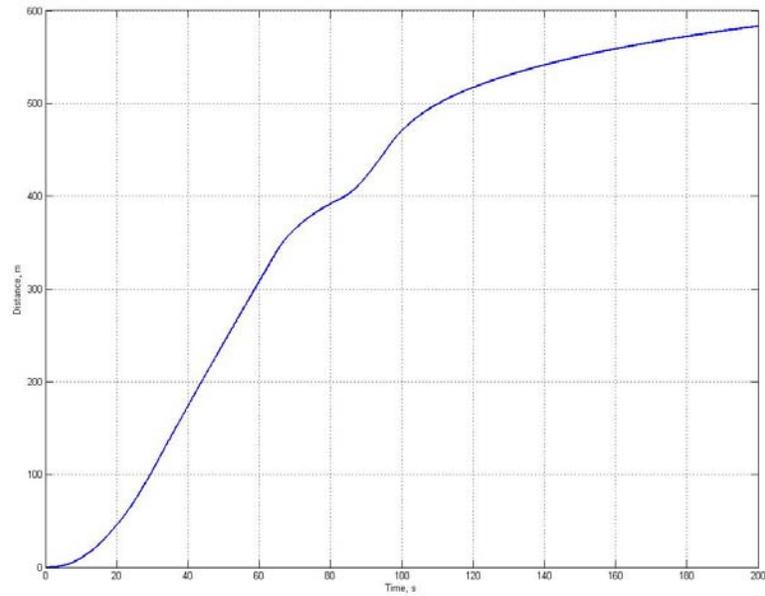


Fig. 7. The distance traveled by laddermill sail, m

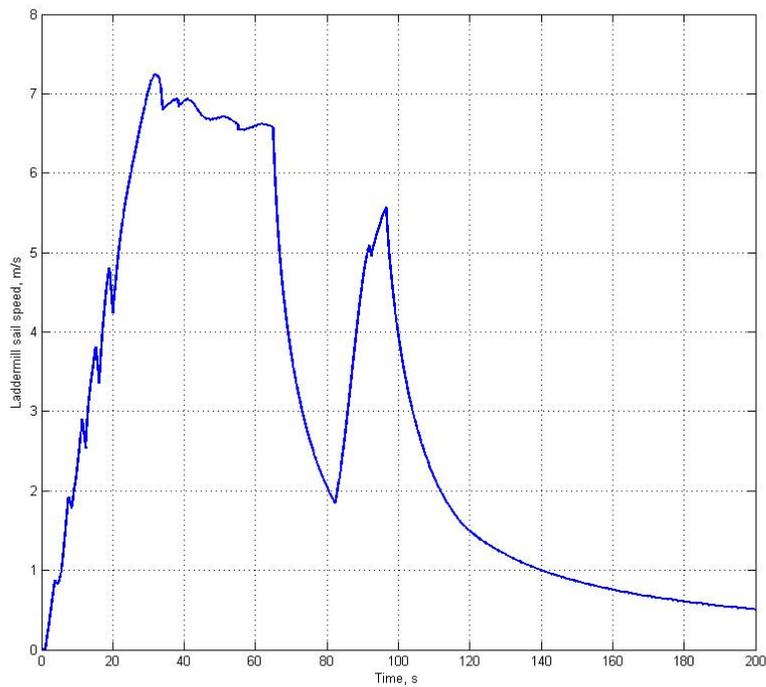


Fig. 8. The speed of laddermill sail relative to the water, m/s

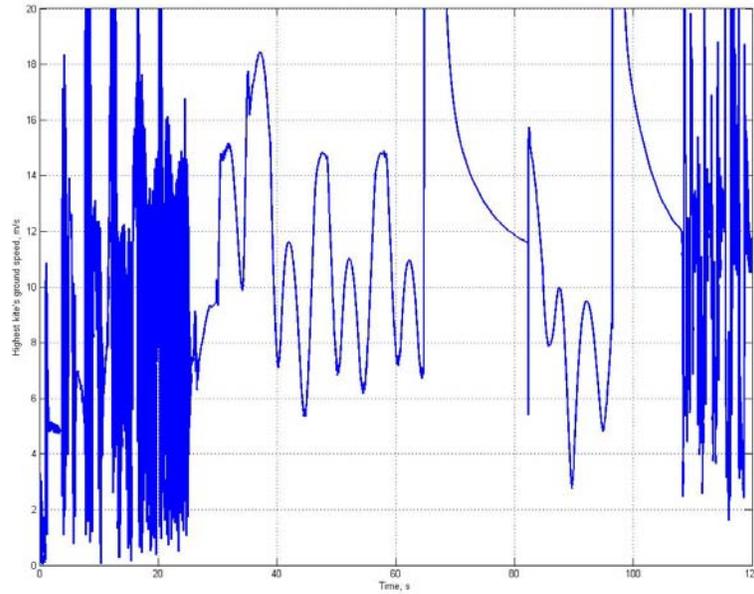


Fig. 9. The speed of the highest kite relative to the ground (kite's ground speed), m/s

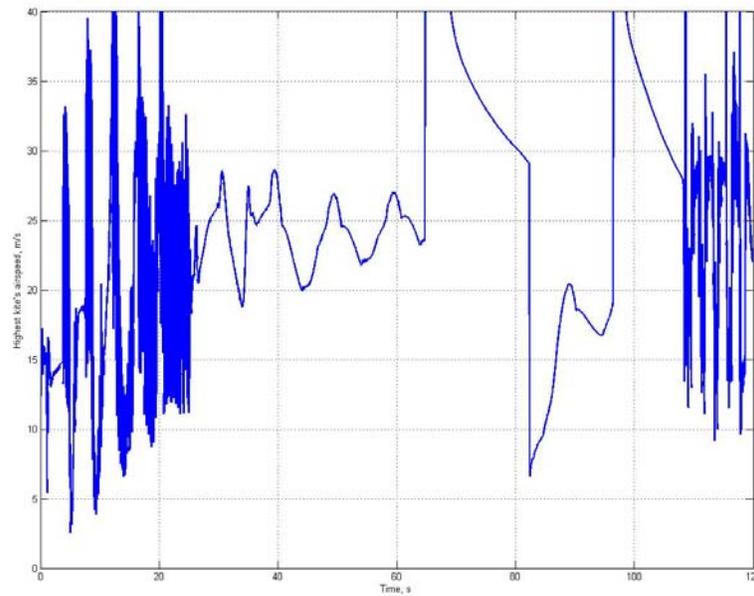


Fig. 10. The speed of the highest kite relative to the airflow (kite's air speed), m/s

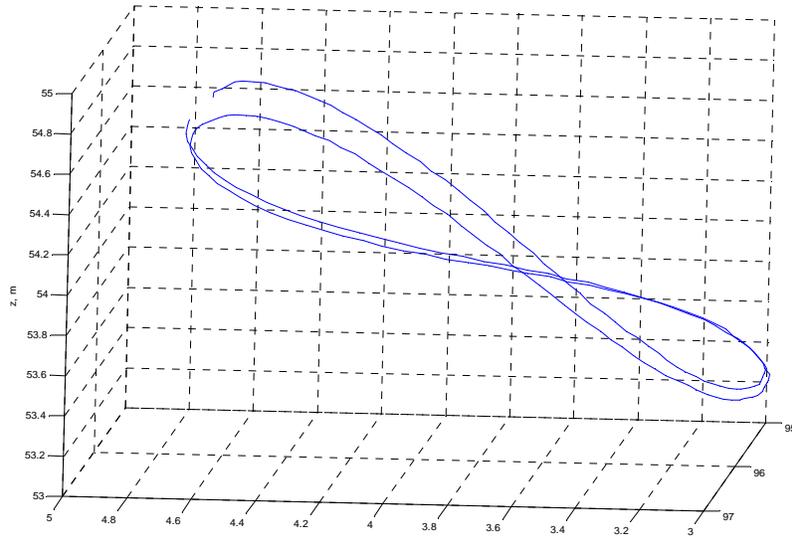


Fig. 11. Trajectory of the highest kite.

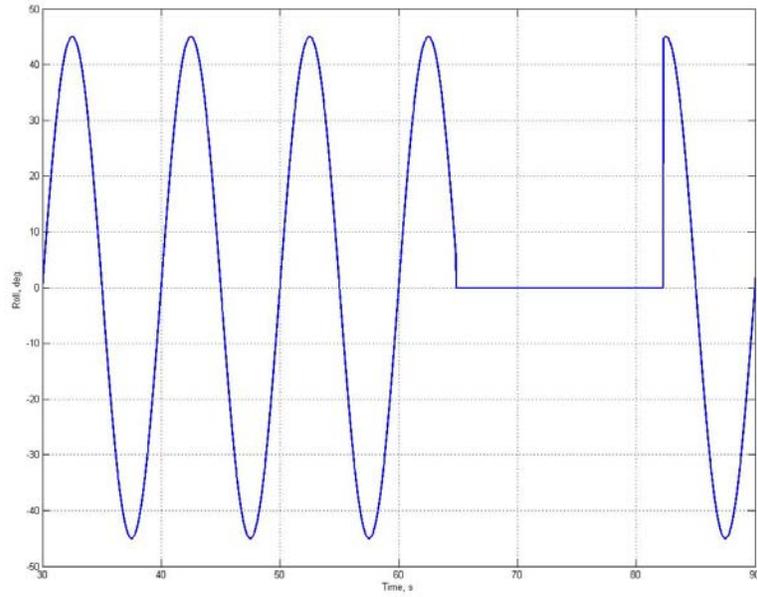


Fig. 12. Highest kite's roll, degress

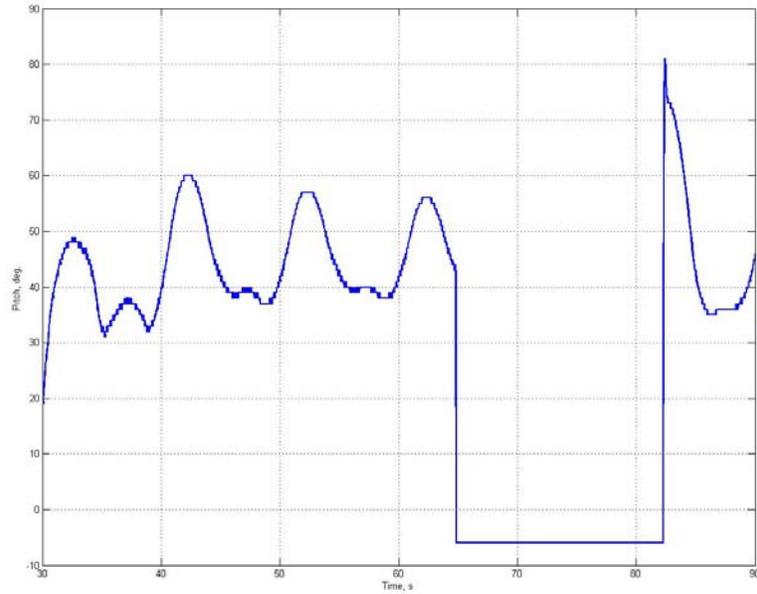


Fig. 13. Highest kite's pitch, degrees

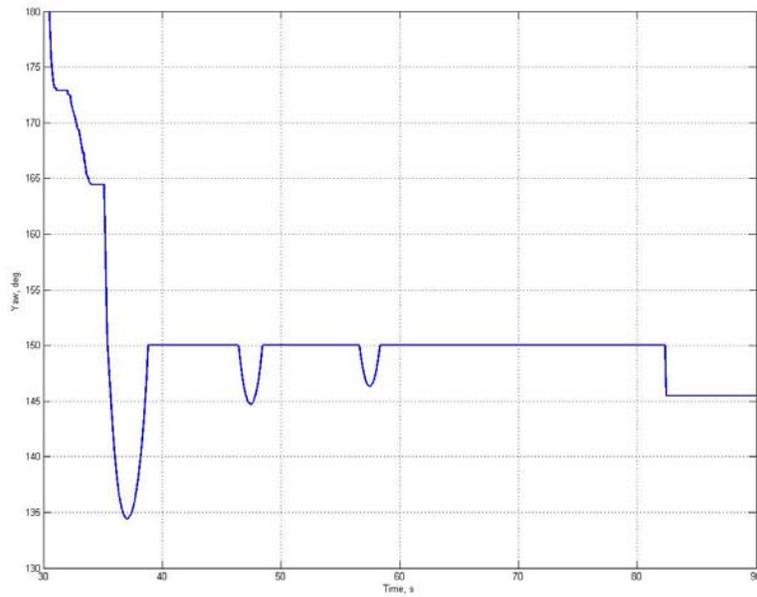


Fig. 14. Highest kite's yaw, degrees